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Azimuthal transverse single-spin asymmetries of inclusive jets and hadrons within jets from polarized pp collisions at $\sqrt{s}$ = 510 GeV

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The study of the origin of transverse single-spin asymmetries has triggered the development of the twist-3 formalism and the transverse-momentum-dependent parton distribution functions (TMDs). Measurements of the azimuthal distribution of identified hadrons within a jet in transversely polarized hadronic interactions provide opportunities to study TMD physics, such as the Collins effect which involves the quark transversity and the Collins fragmentation functions. STAR has reported measurements of the Collins asymmetries from jet + $\pi^{\pm}$ production in transversely polarized pp collisions at a center-of-mass energy of $\sqrt{s}$ = 500 GeV based on data taken in 2011 with an integrated luminosity of 23 pb^{-1}. Additionally, an extensive measurement of azimuthal transverse single-spin asymmetries of inclusive jets and hadrons within jets from transversely polarized pp collisions at $\sqrt{s}$ = 200 GeV was performed using data from 2012 and 2015. In 2017, STAR collected a significantly larger pp dataset with an integrated luminosity of 320 pb^{-1} at $\sqrt{s}$ = 510 GeV, which will further improve the precision of the transverse single-spin asymmetry measurements, especially in the high jet transverse momentum region. In this contribution, we report the preliminary results of azimuthal transverse single-spin asymmetries for inclusive jets and charged pions within jets from transversely polarized pp collisions at $\sqrt{s}$ = 510 GeV.

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1. Introduction

Anomalously large transverse single-spin asymmetry, A_N, for inclusive hadrons has been observed in transversely polarized hadron-hadron collisions at different energies [1]. Leading order perturbative quantum chromodynamics (pQCD) cannot describe such large asymmetry [2]. Presently, there are two QCD frameworks developed to explain the observed asymmetries: the high twist and transverse-momentum-dependent (TMD) formalisms.

The twist-3 formalism utilizes the initial-state and final-state multi-parton correlators within collinear pQCD framework, with a single hard scale, Q, which is much larger than Λ_{QCD} [3, 4]. Unlike twist-3, the TMD formalism utilizes the leading-twist framework of pQCD beyond the collinear assumption, with a large scale Q and a soft scale such as the transverse momentum, p_T. It requires correlations between spin polarization and intrinsic transverse momentum either in the initial state or final state. The Sivers effect and Collins effect are two typical examples of TMD mechanisms. The intial-state Sivers effect requires a correlation between the nucleon spin and the intrinsic transverse momentum, k_T, of the parton inside the nucleon [5]. On the other hand, the final-state Collins effect requires a correlation between the quark spin and the transverse momentum of a hadron relative to the quark direction [6]. In semi-inclusive deep inelastic scattering (SIDIS) and hadronic interaction, the Collins effect is generated by a nonzero transversity coupled to the Collins fragmentation function [7, 8].

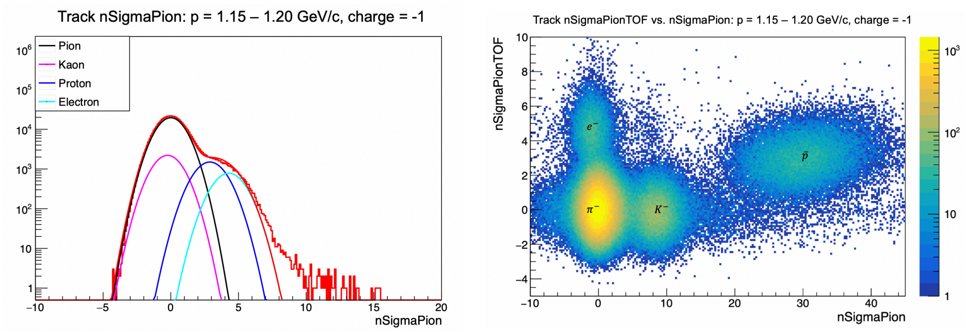
The issue of whether TMD factorization holds or not in the context of transversely polarized pp collisions is discussed in [9–14]. This can be verified by comparing the measured Collins asymmetry against theoretical predictions extracted from global analyses of e^+e^- annihilation and deep inelastic scattering (DIS) processes. Further insight into the potential energy dependence of the Collins effect can be gained by comparing Collins asymmetry at different collision energies.

Previously, STAR has measured the Sivers asymmetry of inclusive jets and Collins asymmetries of hadron in jets in pp collisions at $\sqrt{s}$ = 500 GeV with an integrated luminosity of 23 pb^{-1} [15] and at $\sqrt{s}$ = 200 GeV with an integrated luminosity of 74 pb^{-1} [17]. In this contribution, we report new preliminary results on Sivers asymmetry of jets and charged pion Collins asymmetry with a much larger data sample of 320 pb^{-1} at $\sqrt{s}$ = 510 GeV.

2. Data Analysis

The Relativistic Heavy Ion Collider (RHIC) is currently the world's only facility capable of colliding high energy beams of polarized protons. Transversely polarized proton-proton collision data samples have been taken in recent years at STAR. The dataset used in this analysis was recorded in 2017 at $\sqrt{s}$ = 510 GeV and the proton beam polarization is about 55%. The STAR detectors used in this analysis are the Time Projection Chamber (TPC) [18], Time-of-Flight (TOF) [19] and Electromagnetic Calorimeter (EMC) [20, 21]. The TPC provides charged particle tracking and TOF measures the particle flight time. Both of which provide particle identification. The Barrel and endcap EMC measure the energy deposits from photons, electrons and π^0.

Jets and hadrons within jets are used to probe the transverse single-spin asymmetry since inclusive hadrons are incapable of discriminating between the Sivers and Collins effects. Jet reconstruction utilizes the anti-k_T algorithm with parameter R = 0.5, which follows previous jet



(a) (b)

Figure 1: The particle rich region for TOF unmatched (a) and matched (b) using tracks with momentum range of (1.15, 1.20 GeV/c) as an example.

analysis [15]. Inputs to the jet finder contain charged tracks from the TPC and EMC tower energies. The off-axis cone method [16] is used to estimate the underlying event contribution. The hadron within jet asymmetries are measured with identified charged particles. Particle identification relies on energy loss (dE/dx) obtained through the TPC and the particle's flight time obtained through the TOF. The energy loss, denoted as dE/dx, can be represented as $n\sigma_{dE/dx}$ and is expressed by the following formula:

$$n\sigma_{dE/dx} = \frac{1}{\sigma_{\text{exp}}} \ln\left(\frac{dE/dx_{\text{obs}}}{dE/dx_{\text{cal}}}\right), \tag{1}$$

where dE/dx_{obs} and dE/dx_{cal} are the measured energy loss of charged tracks and the expected energy loss based on the Bichsel formalism, respectively, and σ_{exp} is the TPC dE/dx resolution. Similarly $n\sigma_{TOF}$:

$$n\sigma_{TOF} = \frac{TOF_{\text{meas}} - \frac{L}{c\beta(p)}}{\sigma_{\text{eff}}}, \tag{2}$$

where TOF_{meas} is the measured flight time, $L/c\beta$ is the expected value of the flight time calculated through the path length(L), the speed of light(c), and the inverse velocity($1/\beta$), where $\beta = 1/\sqrt{1 + m^2/p^2}$ and p is the momentum of the particle. σ_{eff} accounts for the time resolution of the TOF detector. In Fig. 1, each particle species rich sample is identified using the TPC and TOF. Figure 1(a) corresponds to tracks without TOF match, where a multi-Gaussian is utilized to fit the $n\sigma_{dE/dx}$ distribution. Figure 1(b) corresponds to tracks matched with a TOF hit, where a two-dimensional multi-Gaussian is used to fit the 2D $n\sigma_{dE/dx}$ vs. $n\sigma_{TOF}$ distribution. The raw asymmetries and particle fractions can be extracted in each particle rich region, and then the pure asymmetries can be calculated through the Moore-Penrose matrix inversion, which is similar to [17].

For $\pi^{\pm}$ within jets in pp collisions, the spin-dependent cross section can be expressed as [24]:

$$
\begin{aligned}
&\frac{d\sigma^{\uparrow}(\phi_S,\phi_H) - d\sigma^{\downarrow}(\phi_S,\phi_H)}{d\sigma^{\uparrow}(\phi_S,\phi_H) + d\sigma^{\downarrow}(\phi_S,\phi_H)} \\
&\propto A_{UT}^{\sin(\phi_S)} \sin(\phi_S) \\
&+ A_{UT}^{\sin(\phi_S-\phi_H)} \sin(\phi_S - \phi_H) \\
&+ A_{UT}^{\sin(\phi_S-2\phi_H)} \sin(\phi_S - 2\phi_H) \\
&+ A_{UT}^{\sin(\phi_S+\phi_H)} \sin(\phi_S + \phi_H) \\
&+ A_{UT}^{\sin(\phi_S+2\phi_H)} \sin(\phi_S + 2\phi_H)\,,
\end{aligned} \tag{3}
$$

where ϕ_S is the angle between the proton spin direction and the reaction plane, ϕ_H is the angle of the $\pi^{\pm}$ momentum transverse to the jet axis relative to the reaction plane. Different angle modulations are related to different effects. The first term, $\sin(\phi_S)$, is related to Sivers effect, and the second term, $\sin(\phi_S - \phi_H)$, is related to the Collins effect. The inclusive jet asymmetry is related to the twist-3 distribution of the k_T-integrated Sivers function [27]. The $A_{UT}^{\sin(\phi_S)}$ for jets containing a π^+ or π^- with a longitudinal momentum fraction $z > 0.3$ can enhance the u and d quark fractions [17, 28, 29]. At low jet p_T, the asymmetries are sensitive to gluonic subprocesses, and with increasing jet p_T, the asymmetries become sensitive to quark subprocesses.

For each modulation, the transverse single-spin asymmetry is extracted using the "cross-ratio" method to cancel detector efficiency and spin-dependent luminosity:

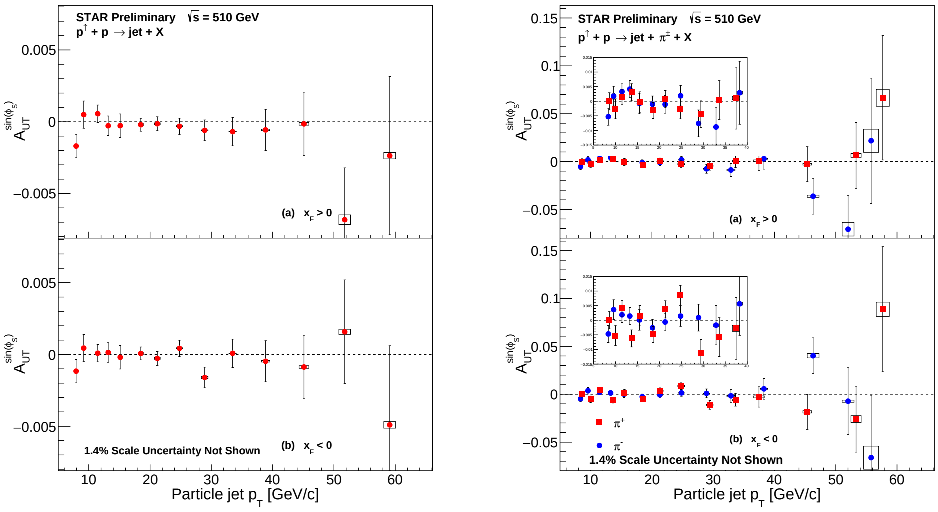
$$
A_N \sin(\phi) = \frac{1}{P} \cdot \frac{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} - \sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}{\sqrt{N^{\uparrow}(\phi)N^{\downarrow}(\phi+\pi)} + \sqrt{N^{\downarrow}(\phi)N^{\uparrow}(\phi+\pi)}}, \tag{4}
$$

where $N^{\uparrow}$ and $N^{\downarrow}$ are the jet or hadron in jet yields for a given spin state, and ϕ is the corresponding angle for the different modulations.

3. Results

The Sivers asymmetry of inclusive jets and jets that contain a charged pion with longitudinal momentum fraction $z > 0.3$ versus particle jet p_T is presented in Fig. 2. Both inclusive jets asymmetry and $\pi^{\pm}$-tagged jet asymmetries are consistent with zero within uncertainties, which is similar to previous STAR results in polarized pp collisions at $\sqrt{s} = 200$ and $\sqrt{s} = 500$ GeV [15, 17].

Figure 3 shows the Collins asymmetries for $\pi^{\pm}$ within a jet as a function of particle jet p_T from pp collisions at $\sqrt{s} = 510$ GeV at STAR taken in 2017. New results are consistent with previous data [15], but with much better statistical precision. The asymmetries are positive for π^+ and negative for π^- because π^+ and π^- are mostly from favored fragmentation of u and d quark, respectively. A global analyses of SIDIS and e^+e^- annihilation indicate that the u quark transversity is positive, while the d quark transversity is negative. The Collins asymmetry only exists for quark subprocesses because the gluon transversity distribution is expressed by the amplitude of the gluon helicity flip [22, 23]. Therefore, the gluon transversity does not exist for spin-1/2 nucleons due to the helicity-conservation constraint. Thus, the asymmetries are small at low jet p_T and increase with increasing jet p_T which is sensitive to gluon-quark subprocesses. Figure 4 shows a comparison of the new Collins asymmetry at $\sqrt{s} = 510$ GeV with the $\sqrt{s} = 200$ GeV results as a function of jet



(a) (b)

Figure 2: The Sivers asymmetries, $A_{UT}^{\sin(\phi_S)}$, of inclusive jets (a) and $\pi^{\pm}$ tagged jets with $z > 0.3$ (b). The top panels shows results for jets that scatter forward relative to the polarized beam ($x_F > 0$), while the bottom panels shows jets that scatter backward to the polarized beam ($x_F < 0$).

$x_T (= 2p_T/\sqrt{s})$. These two results with different beam energies nicely align with the jet x_T scale, indicating almost no energy dependence, which will provide important constraints on the scale evolution.

Figures 5 and 6 show the Collins asymmetries as a function of the charged pion's longitudinal momentum fraction, z, and the charged pion's transverse momentum relative to the jet axis, j_T, respectively in different jet p_T bins. These results provide more detailed constraints on the Collins fragmentation function. Figure 7 shows the comparison of the new Collins asymmetries at $\sqrt{s}$ = 510 GeV with the $\sqrt{s}$ = 200 GeV results, as a function of j_T of the charged pion in different z bins. Once again, these asymmetries are in good agreement, further indicating Collins effect has no energy dependence.

Figure 8 shows the Collins asymmetries at $\sqrt{s}$ = 510/500 GeV in comparison with three sets of model calculations [14, 30], which are based on global analyses of SIDIS and e^+e^- results. Each set assumes robust factorization and universality of the Collins function. The DMP+2013 [30] and KPRY [14] predictions assume no TMD evolution while the KPRY-NLL [14] assumes TMD evolution up to next-to-leading-logarithmic. Overall, the experimental measurements are consistent with theoretical predictions within uncertainty, although the theoretical values are systematically lower than the experimental results.

4. Conclusion

In this contribution, we present the transverse single-spin asymmetries of jets and $\pi^{\pm}$ within jets in pp collisions at $\sqrt{s}$ = 510 GeV with STAR 2017 data, which has 14 times more statistics than the previous measurement. The high precision Collins asymmetries for π^+ and π^- results at $\sqrt{s}$ =

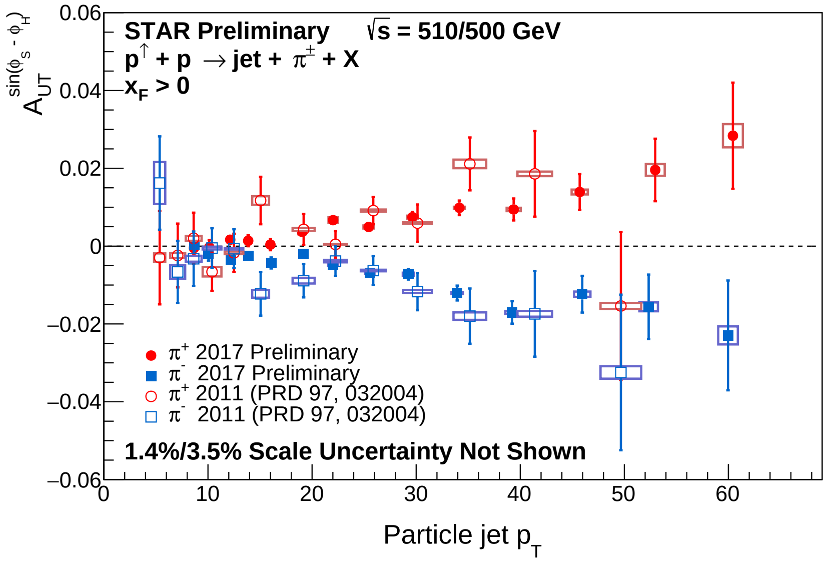


Figure 3: Collins asymmetries, $A_{UT}^{\sin(\phi_S-\phi_H)}$, for $\pi^{\pm}$ in pp collisions at $\sqrt{s}$ = 510/500 GeV. The solid points show the results from this analysis at $\sqrt{s}$ = 510 GeV, while the open points show the STAR previous results at $\sqrt{s}$ = 500 GeV.

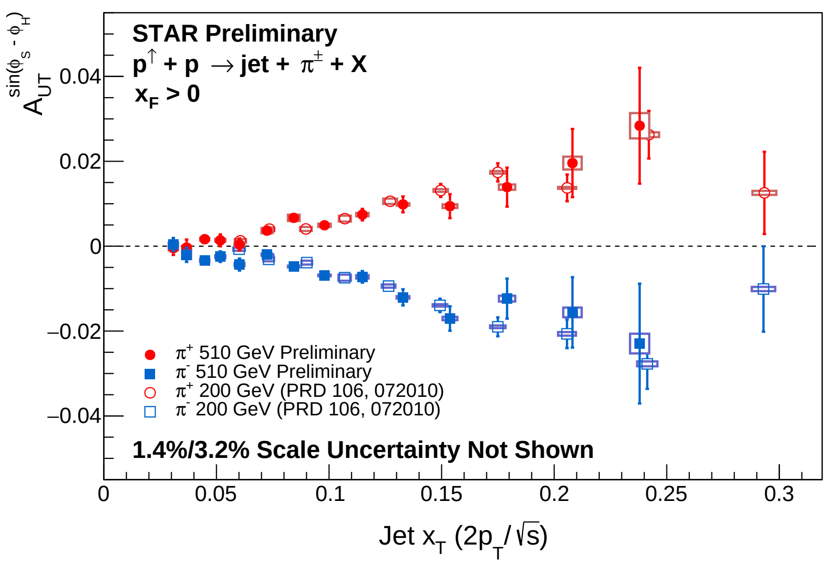


Figure 4: Collins asymmetries, $A_{UT}^{\sin(\phi_S-\phi_H)}$, as a function of particle jet $x_T(=2p_T/\sqrt{s})$. The solid points show the results from this analysis of $\sqrt{s}$ = 510 GeV pp collisions, while the open points show the previous STAR results at $\sqrt{s}$ = 200 GeV [17].

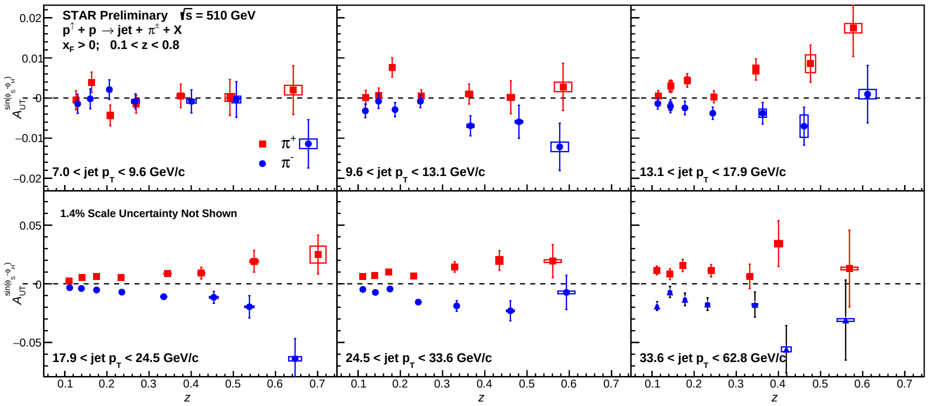


Figure 5: $\pi^{\pm}$ Collins asymmetries, $A_{UT}^{\sin(\phi_S - \phi_H)}$, versus momentum fraction z in pp collisions at $\sqrt{s}$ = 510GeV in different jet-p_T bins.

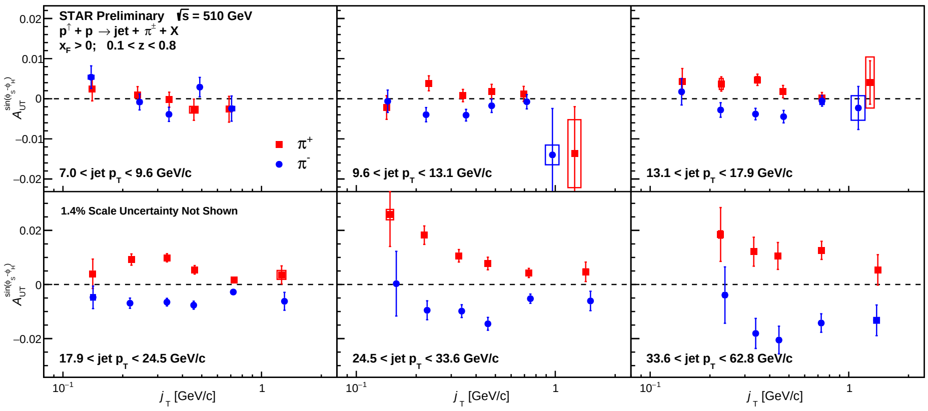


Figure 6: $\pi^{\pm}$ Collins asymmetries, $A_{UT}^{\sin(\phi_S - \phi_H)}$, versus transverse momentum j_T relative to the jet axis in pp collisions at $\sqrt{s}$ = 510GeV in different jet-p_T bins.

510 GeV are in excellent agreement with the 200 GeV results, indicating no energy dependence. Due to an enhancement in statistics, the Collins asymmetries for π^+ and π^- versus z and j_T are extracted. These measurements provide important constraints on the scale evolution, and a test for the universality of the Collins asymmetry. In addition, a large data sample (400 pb^{-1}) with 52% polarization of transversely polarized pp collisions was recorded in 2022 by STAR, with the forward detector ($2.5 < \eta < 4$) installed, which provides a unique opportunity to study the transverse single-spin asymmetry in the forward region.

5. Acknowledgements

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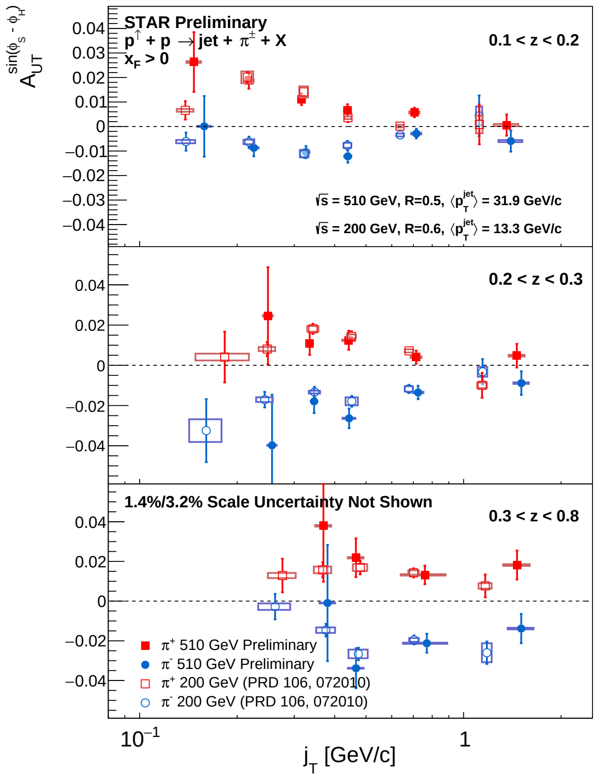

Figure 7: Comparison of $\pi^{\pm}$ Collins asymmetries, $A_{UT}^{\sin(\phi_S-\phi_H)}$, between $\sqrt{s}$ = 510 GeV and $\sqrt{s}$ = 200 GeV versus transverse momentum relative to the jet axis, j_T, in different z bins.

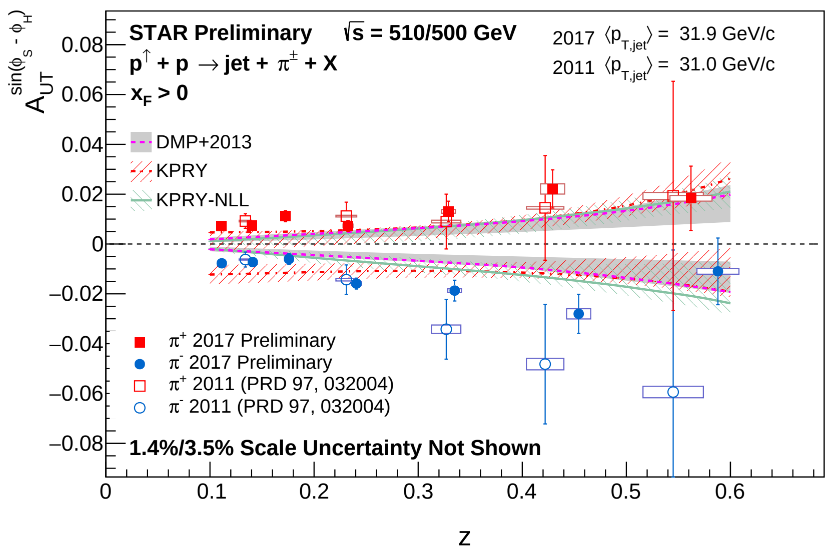

Figure 8: Collins asymmetries, $A_{UT}^{sin(\phi_S-\phi_H)}$, as a function of charged pion's longitudinal momentum fraction, z. The asymmetries are compared with model calculations from Ref. [14, 30]

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